Central Exclusive Diffractive MSSM Higgs-Boson Production at the LHC

S. Heinemeyer[1], **V.A. Khoze**[2,3], **M.G. Ryskin**[2,3], **W.J. Stirling**[2,4], **M. Tasevsky**[5] **and G. Weiglein**[2]

[1]Instituto de Fisica de Cantabria (CSIC-UC), Santander, Spain
[2]IPPP, Department of Physics, Durham University, Durham DH1 3LE, U.K.
[3]Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg, 188300, Russia
[4]Department of Mathematical Sciences, Durham University, DH1 3LE, U.K.
[5]Institute of Physics of the ASCR, v. v. i., Na Slovance 2, CZ-18221, Czech Republic

E-mail: Georg.Weiglein@durham.ac.uk

Abstract. The prospects for central exclusive diffractive (CED) production of MSSM Higgs bosons at the LHC are reviewed. It is shown that the CED channels, making use of forward proton detectors at the LHC installed at 220 m and 420 m distance around ATLAS and / or CMS, can provide important information on the Higgs sector of the MSSM. In particular, CED production of the neutral $\mathcal{CP}$-even Higgs bosons h and H and their decays into bottom quarks has the potential to probe interesting regions of the M_A–$\tan\beta$ parameter plane of the MSSM and may give access to the bottom Yukawa couplings of the Higgs bosons up to masses of $M_H \lesssim 250$ GeV.

1. Introduction

Searches for Higgs bosons and the investigation of their properties are among the main goals of the LHC [1–3]. While the Standard Model (SM) comprises only one Higgs boson, many models of new physics require an extended Higgs sector. The most popular extension of the SM is the Minimal Supersymmetric Standard Model (MSSM), whose Higgs sector consists of two doublets, leading to five physical states. At lowest order the Higgs sector of the MSSM is $\mathcal{CP}$-conserving, containing two $\mathcal{CP}$-even Higgs bosons, h and H, a $\mathcal{CP}$-odd Higgs boson, A, and the charged Higgs bosons $H^{\pm}$. The MSSM Higgs sector can be specified at lowest order in terms of the gauge couplings, the ratio of the two Higgs vacuum expectation values, $\tan\beta \equiv v_2/v_1$, and the mass of the $\mathcal{CP}$-odd Higgs boson, M_A. Higgs physics in the MSSM is affected by large higher-order corrections (see for example Ref. [4] for recent reviews), which have to be taken into account for reliable phenomenological predictions. Revealing that a detected new state is indeed a Higgs boson and distinguishing the Higgs boson(s) of the SM or the MSSM from the states of other theories will be non-trivial. This goal will require a comprehensive programme of precision Higgs measurements. In particular, it will be of utmost importance to determine the spin and $\mathcal{CP}$ properties of a new state and to measure precisely its mass, width and couplings.

The "conventional" LHC production channels, gluon fusion, weak boson fusion and associated production with heavy quarks or vector bosons, could be complemented by "central exclusive diffractive" (CED) Higgs-boson production making use of of forward proton taggers (Roman Pot (RP) detectors) installed at 220 m and 420 m distance around ATLAS and / or CMS [5,6]. In

the exclusive processes $pp \to p{\oplus}H{\oplus}p$, where the $\oplus$ signs are used to denote the presence of large rapidity gaps, there is no hadronic activity between the outgoing protons and the decay products of the central system. If the outgoing protons remain intact and scatter through small angles then, to a very good approximation, the primary active di-gluon system obeys a $J_z = 0$, $\mathcal{CP}$-even selection rule [7]. Here J_z is the projection of the total angular momentum along the proton beam axis. This selection rule readily permits a clean determination of the quantum numbers of the observed Higgs resonance which will be dominantly produced in a scalar state. Furthermore, because the process is exclusive, the energy loss of the outgoing protons is directly related to the mass of the central system, allowing a potentially excellent mass resolution, irrespective of the decay mode of the produced particle. The CED processes would allow all the main Higgs-boson decay modes, $b\bar{b}$, WW and $\tau\tau$, to be observed in the same production channel. This could provide a unique possibility to study the Higgs coupling to bottom quarks, which may be difficult to access in other search channels at the LHC [1–3] despite the fact that $H \to b\bar{b}$ is by far the dominant decay mode for a light SM-like Higgs boson.

Within the MSSM, CED Higgs-boson production can be even more important than in the SM. The coupling of the lightest MSSM Higgs boson to bottom quarks and τ leptons can be strongly enhanced for large values of $\tan\beta$ and relatively small values of M_A. On the other hand, for larger values of M_A the branching ratio of the heavy $\mathcal{CP}$-even Higgs boson into bottom quarks, $\mathrm{BR}(H \to b\bar{b})$, is much larger than for a SM Higgs boson of the same mass. As a consequence, CED Higgs boson production with decay to $b\bar{b}$ can be utilised in the MSSM up to much higher Higgs-boson masses than in the SM case. We briefly review in the following some of the results of Ref. [8], where the prospects for CED production of MSSM Higgs bosons has been analysed in detail (see also Refs. [9–11] for other studies in the MSSM).

2. CED MSSM Higgs-boson production: cross sections, background processes and experimental aspects

The Higgs signal and background cross sections can be written as a function of the Higgs-boson mass with the help of simple approximate formulae [8, 9, 12]. The cross sections $\sigma^{\rm excl}$ for CED production of h, H can be obtained from

$$\sigma^{\rm excl}\,\mathrm{BR}^{\rm MSSM} = 3\,\mathrm{fb}\left(\frac{136}{16+M}\right)^{3.3}\left(\frac{120}{M}\right)^{3}\frac{\Gamma(h/H \to gg)}{0.25\ \mathrm{MeV}}\,\mathrm{BR}^{\rm MSSM}, \tag{1}$$

where we calculate the gluonic partial width $\Gamma(h/H \to gg)$ and the branching ratios for the various channels in the MSSM, $\mathrm{BR}^{\rm MSSM}$, using the program `FeynHiggs` [13]. The mass M (in GeV) denotes either M_h or M_H. The factor $(136/(16+M))^{3.3}$ accounts for the mass dependence of the effective "exclusive" gg^{PP} luminosity, see Refs. [9, 12]. The normalisation is fixed at $M = 120$ GeV, where in accordance with Ref. [9] we obtain $\sigma^{\rm excl} = 3$ fb with the width $\Gamma(H^{\rm SM} \to gg) = 0.25$ MeV. In Ref. [9] various uncertainties in the prediction of the CED cross sections were discussed, leading to an estimate of an uncertainty factor of ~ 2.5 (see also Ref. [8] for a more detailed discussion)[1]. Eq. (1) yields a total number of signal events of about 100 for a SM Higgs boson with $M_{H^{\rm SM}} = 120$ GeV with an integrated luminosity of 60 fb^{-1} if only the forward detector acceptances are accounted for and no cuts and efficiencies in the central detector are imposed (summing over the different Higgs decay channels).

Within the accuracy of the existing calculations [7, 14, 15], the overall background to the 0^+ Higgs signal in the $b\bar{b}$ mode can be approximated by

$$\frac{\mathrm{d}\sigma^B}{\mathrm{d}M} \approx 0.5\,\mathrm{fb/GeV}\left[0.92\left(\frac{120}{M}\right)^{6} + \frac{1}{2}\left(\frac{120}{M}\right)^{8}\right]. \tag{2}$$

[1] Additional uncertainties in the production cross sections of up to $\sim 20\%$ could arise for large $\tan\beta$ due to the imperfect inclusion of NNLO QCD corrections.

This expression summarises several types of background subprocess (see Refs. [14–16] and the discussion in Ref. [8]): the prolific (LO) $gg^{PP} \to gg$ subprocess can mimic $b\bar{b}$ production since one may misidentify the outgoing gluons as b and $\bar{b}$ jets; an admixture of $|J_z| = 2$ production, arising from non-forward going protons, which contributes to the (quark-helicity conserving) LO $gg^{PP} \to b\bar{b}$ background; since the b-quarks have non-zero mass there is a contribution to the $J_z = 0$ (quark-helicity non-conserving) cross section of order m_b^2/E_T^2; there is the possibility of NLO $gg^{PP} \to b\bar{b}g$ (dominantly quark-helicity conserving) background contributions, which for hard gluon radiation at large angles do not obey the selection rules; another potential background source can arise from the interaction of two soft Pomerons.

At high instantaneous luminosity, i.e. $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, the main experimental challenge will be pile-up events that contain protons within the acceptances of the RPs. While single pile-up events would not survive the signal selection cuts (see below), the overlay of two single diffractive events with a hard-scale inclusive non-diffractive event in the central detector could mimic the signal. The pile-up issue is currently under intense study within ATLAS and CMS (for detailed discussions, see Refs. [6, 11]). Possible leverages that could bring the pile-up problem under control are fast timing detectors, precise vertex detectors, the fact that signal and pile-up events possess different track multiplicity properties, and a matching of the whole 4-momentum of the central system (measured in the central detector) to the corresponding values obtained from the forward proton taggers.

At nominal LHC optics, forward proton taggers positioned at a distance ± 420 m from the interaction points of ATLAS and CMS will allow coverage in the proton fractional momentum loss ξ in the range 0.002–0.02, with an acceptance of around 30% for a centrally produced system with a mass around 120 GeV. A combination with the foreseen proton detectors at ± 220 m [5] would significantly increase the physics reach of forward studies enlarging the ξ range up to 0.2. This would be especially beneficial because of the acceptance for higher mass states and improvements in the triggering [6].

The main selection criteria for $h, H \to b\bar{b}$ are either two b-tagged jets or two jets with at least one b-hadron decaying into a muon. Details on the corresponding selection cuts can be found in Refs. [6, 8]. To retain the signal at the Level 1 trigger, the following trigger conditions can be used: (1) Single-sided 220 m RP and at least two jets, each with $E_\mathrm{T} > 40$ GeV, measured in the central detector. (2) A jet with $E_\mathrm{T} > 40$ GeV and at least one muon with $E_\mathrm{T} > 3$ GeV, both measured in the central detector. (3) At least two jets each with $E_\mathrm{T} > 90$ GeV measured in the central detector. (4) Leptonic triggers, requiring electrons or muons in the central detector.

For the process $h, H \to b\bar{b}$, a combination of the triggers 1 and 2 allows the retention of about 65% of the signal events passing the relevant cuts at $M = 120$ GeV and up to 100% at $M = 200$ GeV, while at masses well above 200 GeV the trigger 3 retains the whole signal sample selected by the cuts.

In the numerical analysis below we will consider four luminosity scenarios, 60 fb^{-1}, 60 fb^{-1} eff×2, 600 fb^{-1} and 600 fb^{-1} eff×2. Here 60 fb^{-1} and 600 fb^{-1} refer to running at low and high instantaneous luminosity, respectively, using conservative assumptions for the signal rates and the experimental sensitivities [8]. Improvements on the experimental side and possibly higher signal rates could lead to scenarios where the event rates are higher by a factor of 2, denoted as 60 fb^{-1} eff×2 and 600 fb^{-1} eff×2.

3. Discovery reach

We now discuss the prospects for CED production of the neutral $\mathcal{CP}$-even MSSM Higgs bosons in the M_A–$\tan\beta$ plane of the $M_h^{\max}$ benchmark scenario [17]. Since the lighter $\mathcal{CP}$-even Higgs boson of the MSSM is likely to be detectable also in "conventional" Higgs search channels at the LHC (see for example Refs. [1, 3]), it may not be necessary to require a statistical significance as high as 5σ for the CED channel. Therefore in the left plot of Fig. 1 we display contours of 3σ

statistical significances for the four luminosity scenarios defined in Sect. 2. While the region of high $\tan\beta$ and low M_A can be probed also with lower integrated luminosity, in the 600 fb^{-1} eff$\times$2 scenario the coverage extends over nearly the whole M_A–$\tan\beta$ plane, with the exception of a small parameter region around $M_A \approx 140$ GeV. The coverage therefore includes the case of a light SM-like Higgs, which corresponds to the region of large M_A in the plot. As a consequence, if the CED channel can be utilised at high instantaneous luminosity (which requires in particular that pile-up background is brought under control, see the discussion above) this channel can contribute very important information on the Higgs sector of the MSSM. Besides giving access to the bottom Yukawa coupling, which is a crucial input for determining all other Higgs-boson couplings [18], observation of a Higgs boson in CED production with subsequent decay into bottom quarks would provide information on the $\mathcal{CP}$ quantum numbers of the new state, yield an (additional) precise mass measurement, and may even allow a direct measurement of the Higgs-boson width.

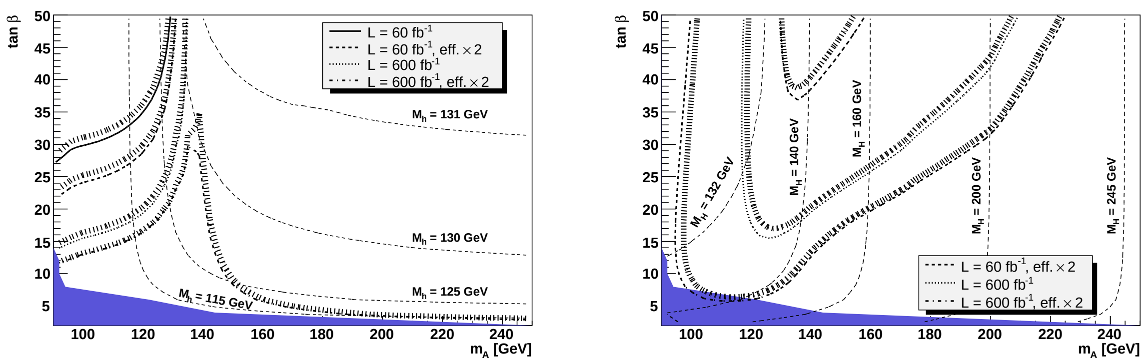

Figure 1. 3σ statistical significance contours for the $h \to b\bar{b}$ channel (left plot) and 5σ discovery contours for the $H \to b\bar{b}$ channel (right plot) in CED production in the M_A–$\tan\beta$ plane of the MSSM within the $M_h^{\max}$ benchmark scenario with $\mu = +200$ GeV. The results are shown for assumed effective luminosities (see text, combining ATLAS and CMS) of 60 fb^{-1}, 60 fb^{-1} eff$\times$2, 600 fb^{-1} and 600 fb^{-1} eff$\times$2. The values of M_h (left plot) and M_H (right plot) are indicated by contour lines. The dark shaded (blue) region corresponds to the parameter region that is excluded by the LEP Higgs searches in the channel $e^+e^- \to Z^* \to Zh, H$ [19]. No exclusion limits from the Higgs searches at the Tevatron are shown, since at present the parameter region with $M_A \gtrsim 100$ GeV and $\tan\beta \lesssim 50$ is hardly affected by the Tevatron exclusion bounds.

The properties of the heavier $\mathcal{CP}$-even Higgs boson of the MSSM differ very significantly from the ones of a SM Higgs in the region where $M_H, M_A \gtrsim 150$ GeV. While for a SM Higgs the BR($H \to b\bar{b}$) is strongly suppressed in this mass region, the decay into bottom quarks is the dominant decay mode for the heavier $\mathcal{CP}$-even MSSM Higgs boson (as long as no decays into supersymmetric particles or lighter Higgs bosons are open). The discovery reach in the "conventional" search channels at the LHC, in particular $b\bar{b}H/A, H/A \to \tau^+\tau^-$, covers the parameter region of high $\tan\beta$ and not too large M_A [1–3], while a "wedge region" [1, 3, 20] remains where the heavy MSSM Higgs bosons escape detection at the LHC.

The right plot of Fig. 1 shows the 5σ discovery contours for the $H \to b\bar{b}$ channel in the $M_h^{\max}$ scenario. In the "600 fb^{-1} eff$\times$2" scenario the discovery reach for the heavier $\mathcal{CP}$-even Higgs boson goes beyond $M_H \approx 200$ GeV in the large $\tan\beta$ region at the 5σ level (at the 3σ level, see Ref. [8], the coverage extends to about $M_H = 250$ GeV for $\tan\beta \approx 50$). Thus, CED production of the heavier $\mathcal{CP}$-even Higgs boson of the MSSM with subsequent decay into bottom quarks provides a unique opportunity for accessing its bottom Yukawa coupling in a mass range where for a SM Higgs boson the decay rate into bottom quarks would be negligibly small. It

is interesting to note that in the "600 $\mathrm{fb}^{-1}\,\mathrm{eff}\times 2$" scenario the ($5\sigma$ level) discovery of a heavy $\mathcal{CP}$-even Higgs boson with a mass of about 140 GeV will be possible for all values of $\tan\beta$.

In conclusion, the CED channels have an interesting physics potential for probing the MSSM Higgs sector. Further experimental and theoretical efforts in exploring this possibility are desirable.

Acknowledgements
Work supported in part by the European Community's Marie-Curie Research Training Network under contract MRTN-CT-2006-035505 'Tools and Precision Calculations for Physics Discoveries at Colliders' (HEPTOOLS).

[1] ATLAS Collaboration, *Detector and Physics Performance Technical Design Report*, CERN/LHCC/99-15 (1999), see: `atlasinfo.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html` .
[2] M. Schumacher, *Czech. J. Phys.* **54** (2004) A103; arXiv:hep-ph/0410112; V. Büscher and K. Jakobs, *Int. J. Mod. Phys.* **A 20** (2005) 2523 [arXiv:hep-ph/0504099].
[3] CMS Collaboration, *Physics Technical Design Report, Volume 2. CERN/LHCC 2006-021*, see: `cmsdoc.cern.ch/cms/cpt/tdr/` .
[4] M. Carena and H. Haber, *Prog. Part. Nucl. Phys.* **50** (2003) 63 [arXiv:hep-ph/0208209]; S. Heinemeyer, W. Hollik and G. Weiglein, *Phys. Rept.* **425** (2006) 265 [arXiv:hep-ph/0412214]; S. Heinemeyer, *Int. J. Mod. Phys.* **A 21** (2006) 2659 [arXiv:hep-ph/0407244]; A. Djouadi, arXiv:hep-ph/0503172; arXiv:hep-ph/0503173.
[5] V. Berardi et al. [TOTEM Collaboration], TDR, CERN-LHCC-2004-002, TOTEM-TDR-001, January 2004; RP220 project at ATLAS, see: `cern.ch/project-rp220` .
[6] CMS and TOTEM diffractive and forward physics working group, CERN/LHCC 2006-039/G-124, CMS Note 2007/002, TOTEM Note 06-5, December 2006; M. Albrow et al., CERN-LHCC-2005-025.
[7] V.A. Khoze, A.D. Martin and M. Ryskin, *Eur. Phys. J.* **C 19** (2001) 477 [Erratum-ibid. **C 20** (2001) 599], hep-ph/0011393.
[8] S. Heinemeyer, V.A. Khoze, M. Ryskin, W.J. Stirling, M. Tasevsky and G. Weiglein, to appear in *Eur. Phys. J.* **C**, arXiv:0708.3052 [hep-ph].
[9] A. Kaidalov, V.A. Khoze, A.D. Martin and M. Ryskin, *Eur. Phys. J.* **C 33** (2004) 261, hep-ph/0311023.
[10] V.A. Khoze, A.D. Martin and M. Ryskin, *Eur. Phys. J.* **C 34** (2004) 327, hep-ph/0401078; J. Ellis, J. Lee and A. Pilaftsis, *Phys. Rev.* **D 70** (2004) 075010 [arXiv:hep-ph/0404167]; *Phys. Rev.* **D 71** (2005) 075007 [arXiv:hep-ph/0502251]; M. Boonekamp, J. Cammin, S. Lavignac, R. Peschanski and C. Royon, *Phys. Rev.* **D 73** (2006) 115011, hep-ph/0506275.
[11] B. Cox, F. Loebinger and A. Pilkington, arXiv:0709.3035 [hep-ph].
[12] A. Kaidalov, V.A. Khoze, A.D. Martin and M. Ryskin, *Eur. Phys. J.* **C 31** (2003) 387, hep-ph/0307064.
[13] S. Heinemeyer, W. Hollik and G. Weiglein, *Comp. Phys. Commun.* **124** 2000 76, hep-ph/9812320. The code is accessible via `www.feynhiggs.de` ; S. Heinemeyer, W. Hollik and G. Weiglein, *Eur. Phys. J.* **C 9** (1999) 343, hep-ph/9812472; G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, *Eur. Phys. J.* **C 28** (2003) 133, hep-ph/0212020; M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak and G. Weiglein, *JHEP* **0702** (2007) 047, hep-ph/0611326.
[14] A. De Roeck, V.A. Khoze, A.D. Martin, R. Orava and M. Ryskin, *Eur. Phys. J.* **C 25** (2002) 391 [arXiv:hep-ph/0207042].
[15] V.A. Khoze, M. Ryskin and W.J. Stirling, *Eur. Phys. J.* **C 48** (2006) 797, hep-ph/0607134.
[16] V.A. Khoze, A. Kaidalov, A.D. Martin, M. Ryskin and W.J. Stirling, published in *Gribov memorial volume* 129-144, Budapest 2005, arXiv:hep-ph/0507040; V.A. Khoze, A.D. Martin and M.G. Ryskin, arXiv:0705.2314 [hep-ph].
[17] M. Carena, S. Heinemeyer, C. Wagner and G. Weiglein, *Eur. Phys. J.* **C 26** (2003) 601, hep-ph/0202167; *Eur. Phys. J.* **C 45** (2006) 797, hep-ph/0511023.
[18] M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein and D. Zeppenfeld, *Phys. Rev.* **D 70** (2004) 113009, [arXiv:hep-ph/0406323].
[19] G. Abbiendi et al. [ALEPH, DELPHI, L3, OPAL Collaborations and LEP Working Group for Higgs boson searches], *Phys. Lett.* **B 565** (2003) 61, hep-ex/0306033; S. Schael et al. [ALEPH, DELPHI, L3, OPAL Collaborations and LEP Working Group for Higgs boson searches], *Eur. Phys. J.* **C 47** (2006) 547, hep-ex/0602042.
[20] S. Gennai, S. Heinemeyer, A. Kalinowski, R. Kinnunen, S. Lehti, A. Nikitenko and G. Weiglein, *Eur. Phys. J.* **C 52** (2007) 383, arXiv:0704.0619 [hep-ph].